Lunar Surface Systems Concepts Studies

THERMAL ENERGY STORAGE

U.S. Chamber of Commerce
February 26, 2009

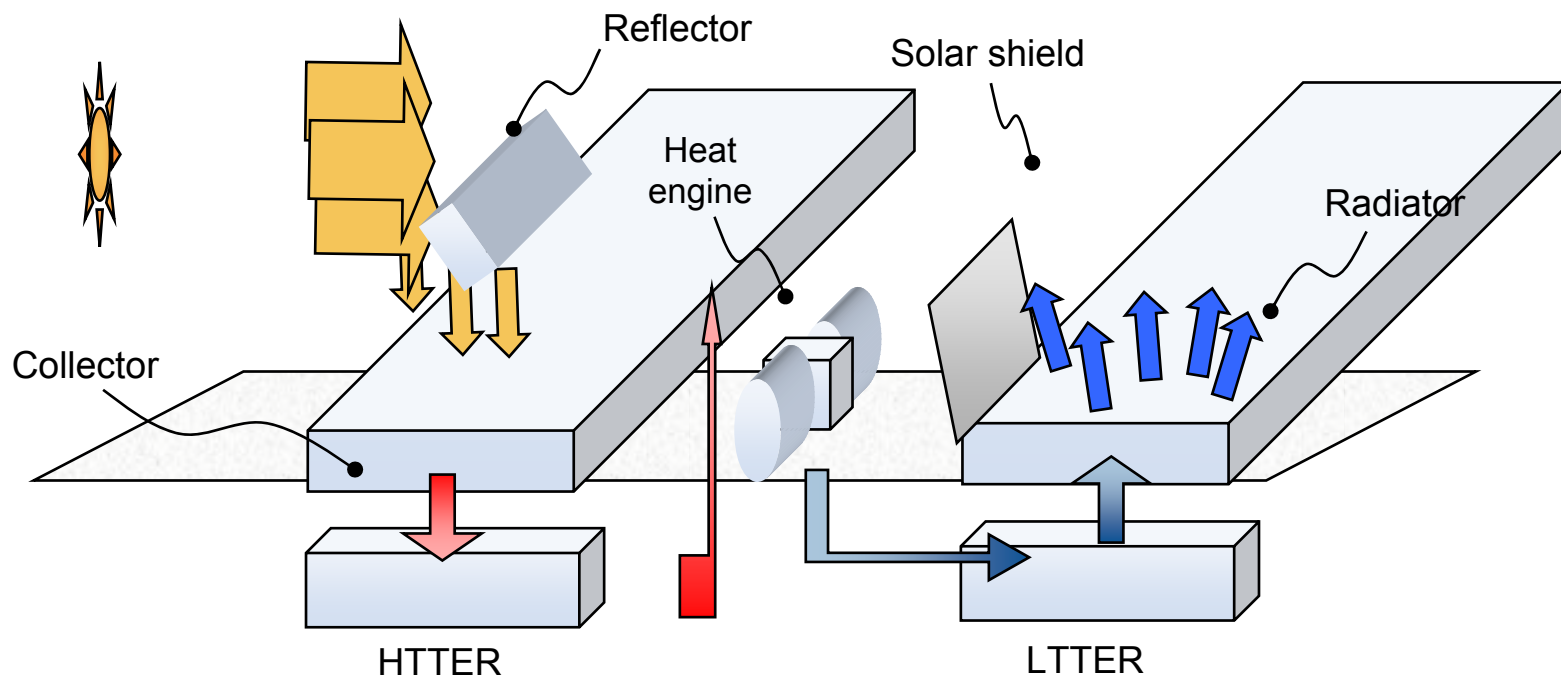Robert S. Wegeng (PI)   James H. Saunders (Co-PI)

Christopher J. Pestak   Ioan I. Feier
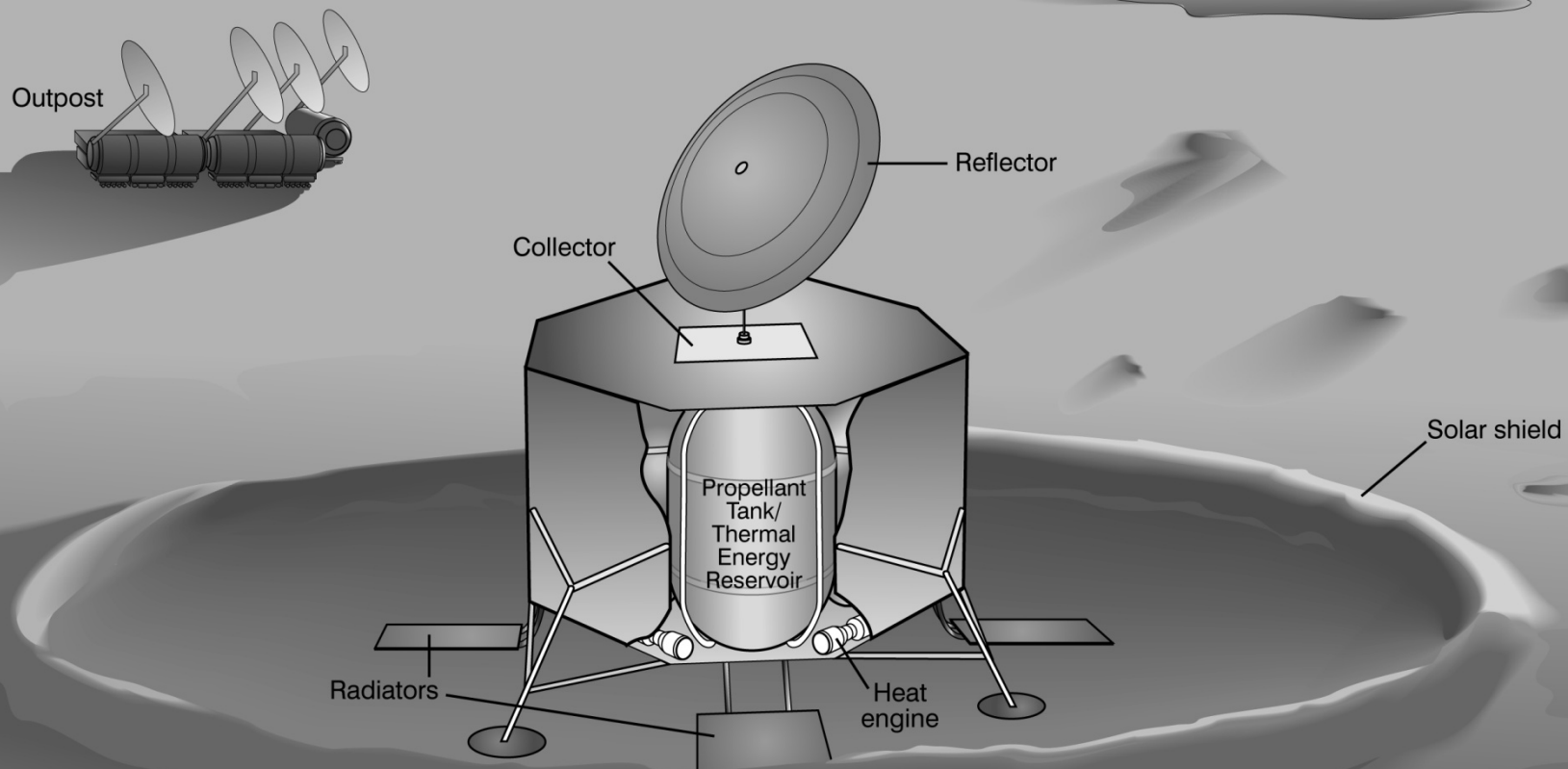
Paul Humble

TER System Concept

TER – Thermal Energy Reservoir
HTTER – High Temperature Thermal Energy Reservoir
LTTER – Low Temperature Thermal Energy Reservoir

Battelle Conceptual Design

Battelle Conceptual Design

- Makes use of Altair Lander propellant tanks

- Makes use of ISRU byproducts (e.g. from O_2 generation)

- Requires no reactants to be brought from Earth

- Net power generation capacity: 8.0 kWe

- Net Power Density: ~8-11 watts/kg

Outline

- Introduction

- Battelle Overview

- Technical Background

- Analytical Support for Reference System Conceptual Design

- Additional Applications of Lunar TERs (Not part of Contract Scope)

- Conclusions

Why We Do What We Do – Battelle's Beginnings

- ▶ Founded by Will of Gordon Battelle in 1929 as a non-profit, charitable trust to provide "the greatest good to humanity"

- ▶ Governed by a self-perpetuating Board of Directors

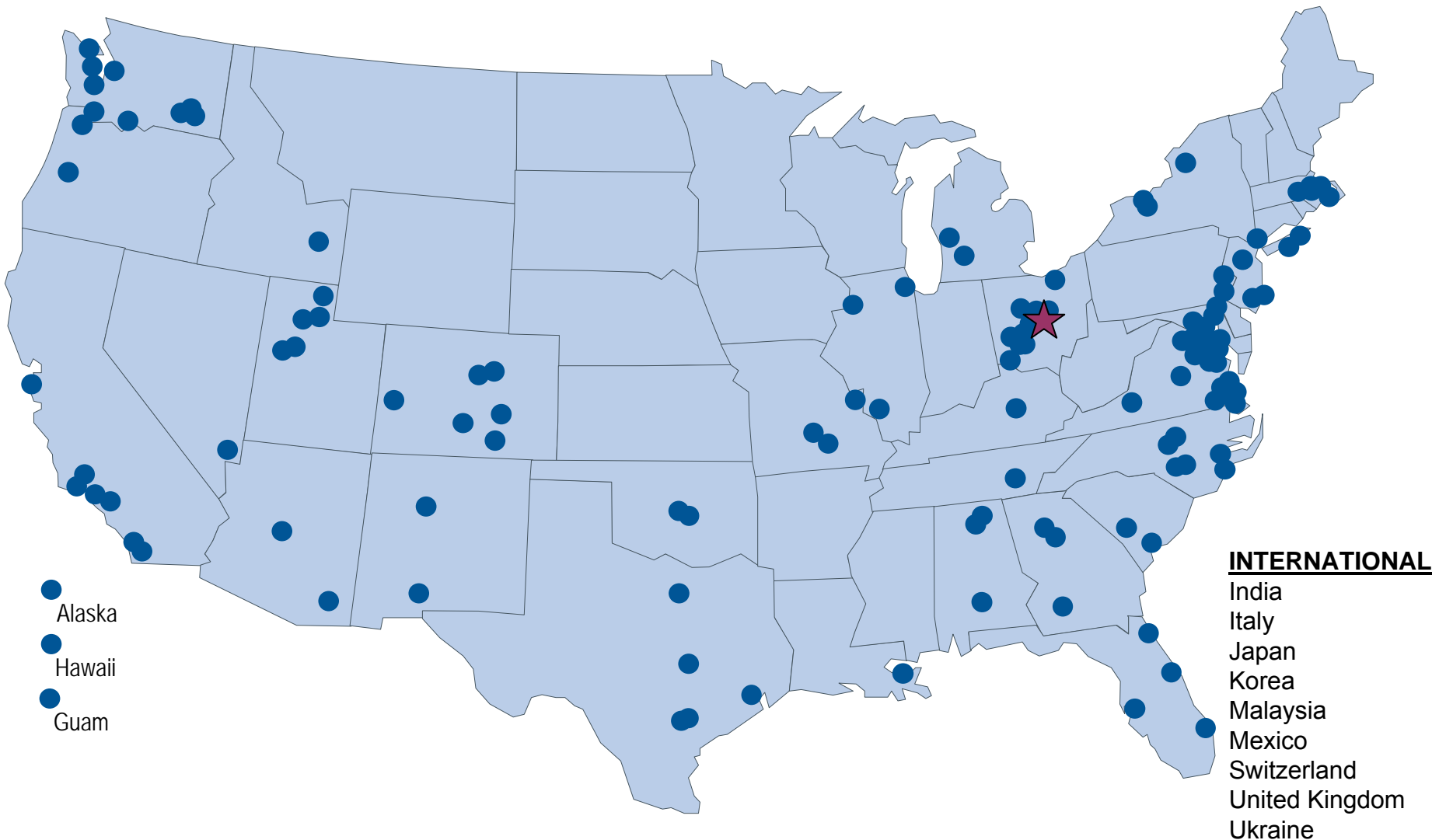- ▶ Interprets Will in light of today's needs and conditions

Purposes outlined in Will:

- "Creative and research work"

- "Making of discoveries and inventions"

- Better education of men and women for employment

- Societal and economic impact

Battelle Locations

INTERNATIONAL
India
Italy
Japan
Korea
Malaysia
Mexico
Switzerland
United Kingdom
Ukraine

Alaska

Hawaii

Guam

Major Technology Centers

Battelle Europe
Geneva, Switzerland

Battelle Corporate Headquarters
Columbus, Ohio

Battelle Eastern Science and Technology Center
Aberdeen, Maryland

Ocean Sciences Laboratory
Duxbury, Massachusetts

National Biodefense Analysis and Countermeasures Center
Ft. Detrick, Maryland

Marine Sciences Laboratory
Sequim, Washington

Major Technology Centers (Cont.)

Brookhaven National Laboratory
Upton, New York

Pacific Northwest National Laboratory
Richland, Washington

Oak Ridge National Laboratory
Oak Ridge, Tennessee

National Renewable Energy Laboratory
Golden, Colorado

Idaho National Laboratory
Idaho Falls, Idaho

Lawrence Livermore National Laboratory
Livermore, California

Technical Background
Requirements

- 2 to 5 kW$_e$ net discharge electric power

- 100 to 2000 kW$_e$-hr net energy storage per module

- TRL 6 by 2015 – 2018 timeframe

- Operational life of 10,000 to 15,000 hours

- 100 to 2000 charge/discharge cycles

- Ability to withstand high dust, radiation and widely varying thermal environment

Motivations

- Thermal Energy Reservoirs utilize the diurnal cycle of the Moon to generate electricity

  – Temperature swings of ~100 K to ~400K (equatorial regions)

  – With concentrated solar energy, the high temperature reservoir can be made to be hotter

- The majority of the mass of a lunar TER is already on the Moon

Motivations

- Synergistic with other lunar assets/programs

  – Considers using processed lunar regolith, a byproduct of ISRU, as thermal mass material

  – Considers using Altair Descent Stage propellant tanks to house thermal mass

  – Considers use of high efficiency Stirling Cycle heat engine

    - International Lunar Network

    - Terrestrial solar-thermal power generation

Courtesy of Infinia Corporation

Technical Background
Thermal Energy Storage Concept
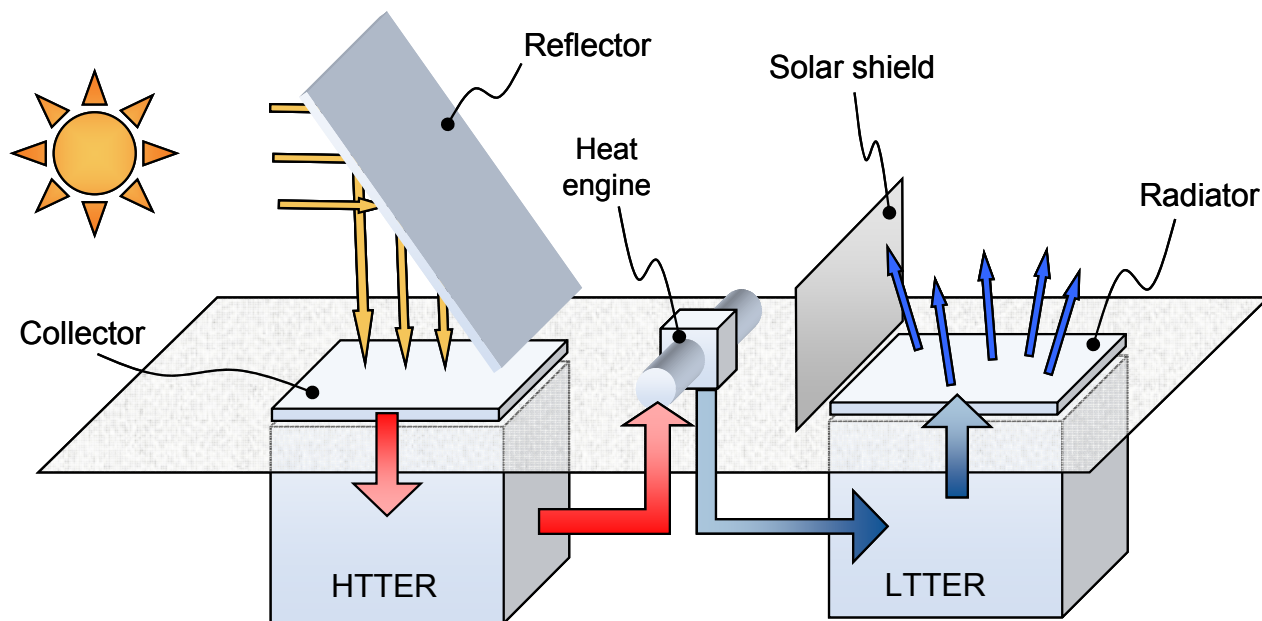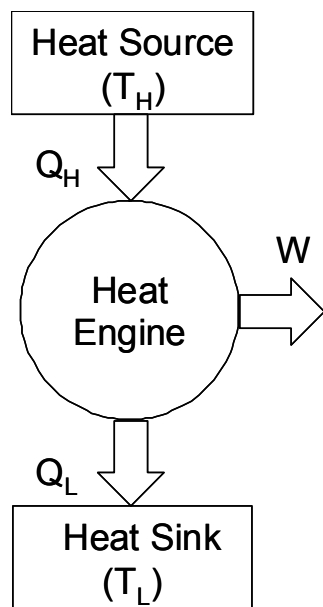
Thermal Mass (TM) Materials

- ## Native lunar regolith is a poor thermal mass material
  - ### Thermal properties similar to fiberglass insulation

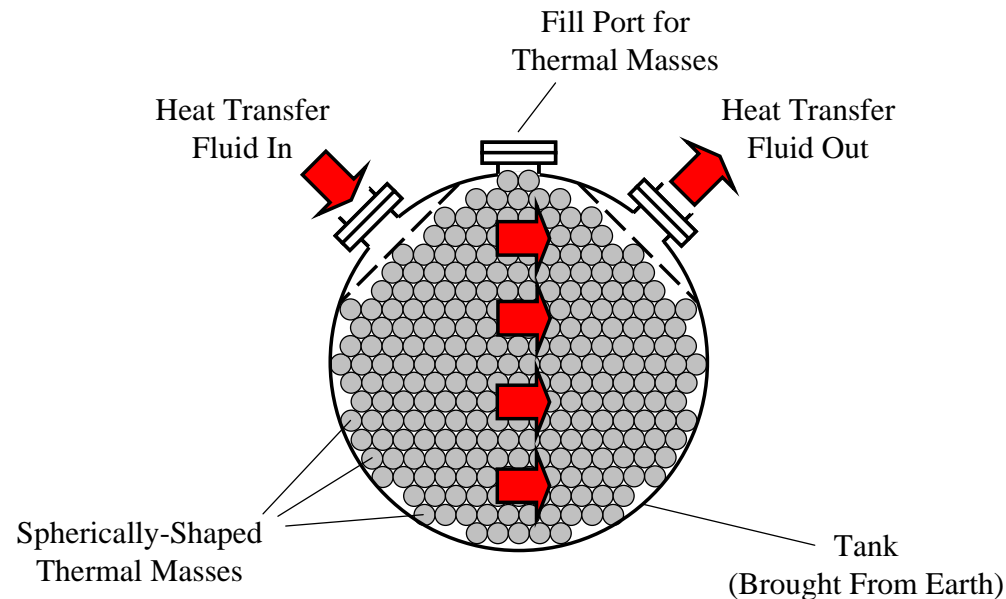- ## Regolith can be processed to yield improved thermal properties

		THERMAL PROPERTIES		
MATERIAL	**Density** (kg/m^3)	**Specific Heat** $(J/kg\text{-}K)$	**Thermal Diffusivity** (m^2/sec)	**Thermal Interaction Distance over 354 hours** (m)
Native Lunar Regolith	1.8×10^3	8.40×10^2	6.6×10^{-9}	0.183
Solid Basalt Rock	3×10^3	8.00×10^2	8.7×10^{-7}	2.11
Common Brick	1.92×10^3	8.35×10^2	4.49×10^{-7}	1.51

Technical Background
Thermal Mass Production Methods

- Compaction and sintering (e.g., microwave sintering)

- Melting processed or unprocessed regolith, then solidifying the melt into a solid block

- Incorporating hardware and/or materials with high thermal conductivity and/or high thermal capacity (e.g., heat pipes, phase-change materials)

- Reducing regolith by thermochemical or electrochemical means, to produce a metal-enriched product

Fill Port for
Thermal Masses

Heat Transfer
Fluid In

Heat Transfer
Fluid Out

Spherically-Shaped
Thermal Masses

Tank
(Brought From Earth)

LSAM/Altair Descent Stage LOX/H2 Tank Volume Estimates

	Tank Void Volume*	Thermal Mass Capacity		
	m^3	m^3	kg	kw-hr$_t$ per 100 C
1 O_2 tank	5.655	3.393	8143	185.5
1 H_2 Tank	16.745	10.047	24,113	549.2
1 H_2 tank + 1 O_2 tank	22.40	13.44	32,256	734.7
2 H_2 tanks	33.49	20.094	48,256	1098.5
2 H_2 tanks + 1 O_2 tank	39.145	23.487	56,369	1284.0
2 H_2 tanks + 2 O_2 tanks	44.8	26.88	64,512	1469.4

Descent Module Main Propulsion System

Main Propellant Tank, LH2 (4 PLCS)

...nifold

... Manifold

Main Propellant Tank, LOX (4 Plcs)
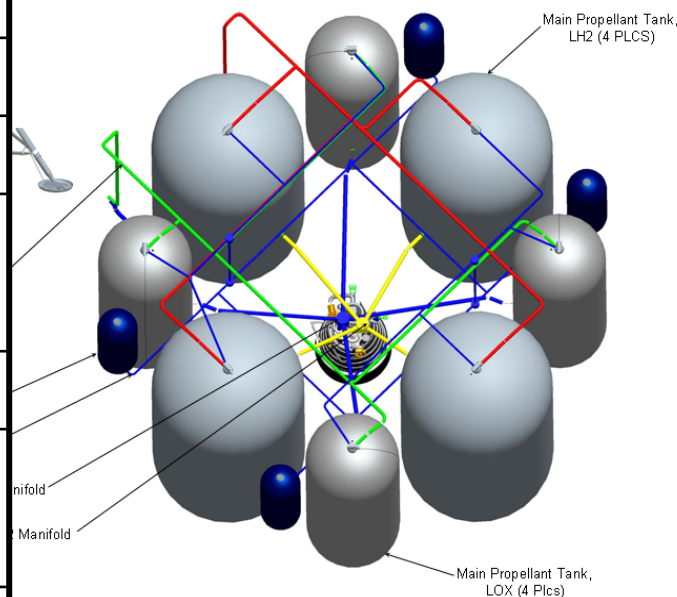
* Provided by Kriss Kennedy and Gary Spexarth, email 12/11/2008

Example Capacity Calculation (Approx)

- *What power level can be obtained while extracting heat in a way that decreases the temperature of the HT TER by 100 C?*

- Assume 1 H_2 tank + 1 O_2 tank

  32,256 kg thermal mass

  734.7 kw-hr_t per 100 C

- Assume 20% efficient heat engine operating for 52 hours, with 90% shaft-work to electricity efficiency

  Power   = 734.7 kw-hr_t x 0.20 / 52 hours = 2.83 kW$_{shaft\ work}$

               = 2.54 kW$_e$

Reference System Configuration

Reference System
• Stirling Cycle Heat Engine

Reference System
• Radiator with Solar Shield
Alternative
• Radiator is integrated with LTTER

Reflector

Solar

Heat engine

Radiator

Reference System
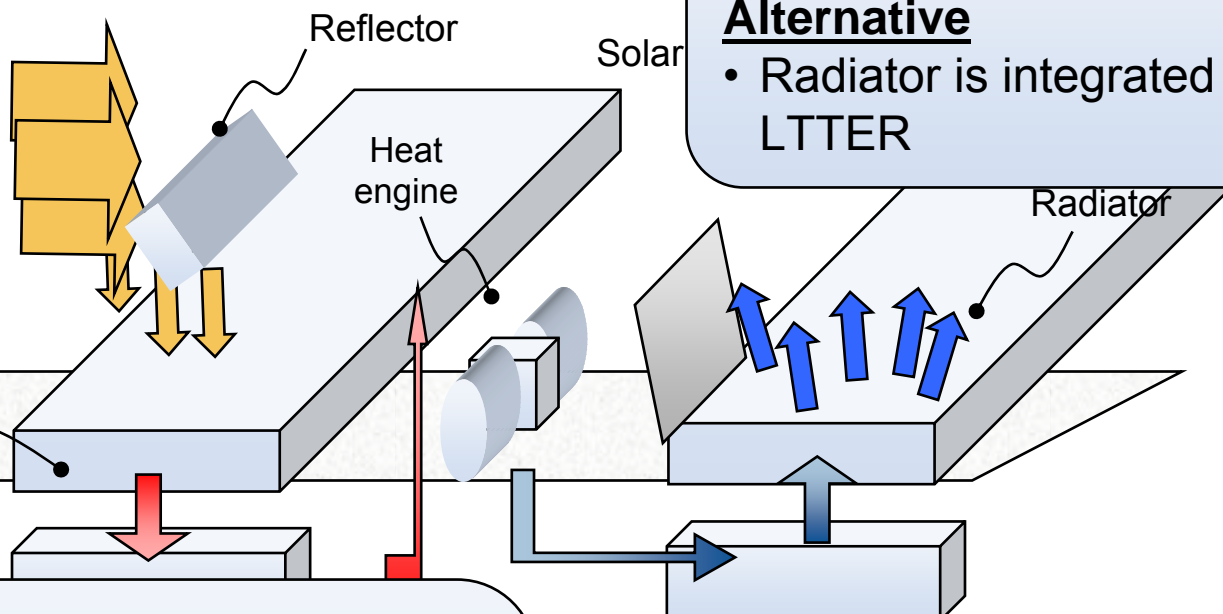• Thin-Film Concentrator (above ground) with Flat Plate Collector

Reference System
•TM consists of Processed Lunar Regolith
•TM in Propellant Tanks
Alternative
•TM bricks interleaved with Heat Exchanger Plates

Reference System
• TM in Propellant Tanks
Alternative
• TM is integrated with Radiator

Analysis of the Conceptual Design
## Jim Saunders
Battelle - Columbus

Analytical Approach

- Goal: Develop system models to estimate mass, volume and performance of thermal energy storage module based power systems for the lunar night.

- System models

  - Lumped parameter models based upon component description

    - Subsytem or component models or parameterizations

  - Simulate charging of the TER during the lunar daytime and power generation during the night.

- Calculations yield encouraging power densities.

  - Launch mass: no fuel to be carried.

System Configuration

- Non-polar region: 348 hr day and night

- South Pole Shackleton Crater:

  - 52 hr max night. Simulations with 52 hr day and night.

  - Seasonal simulations

- Assume 2 kW$_e$, 90 % power electronics efficiency, 200 W parasitics, which yields 2440 W shaft power.

- Later, we'll find that we can combine four 2kW$_e$ into the lander tanks to yield an 8 kW$_e$ system.

Configurations
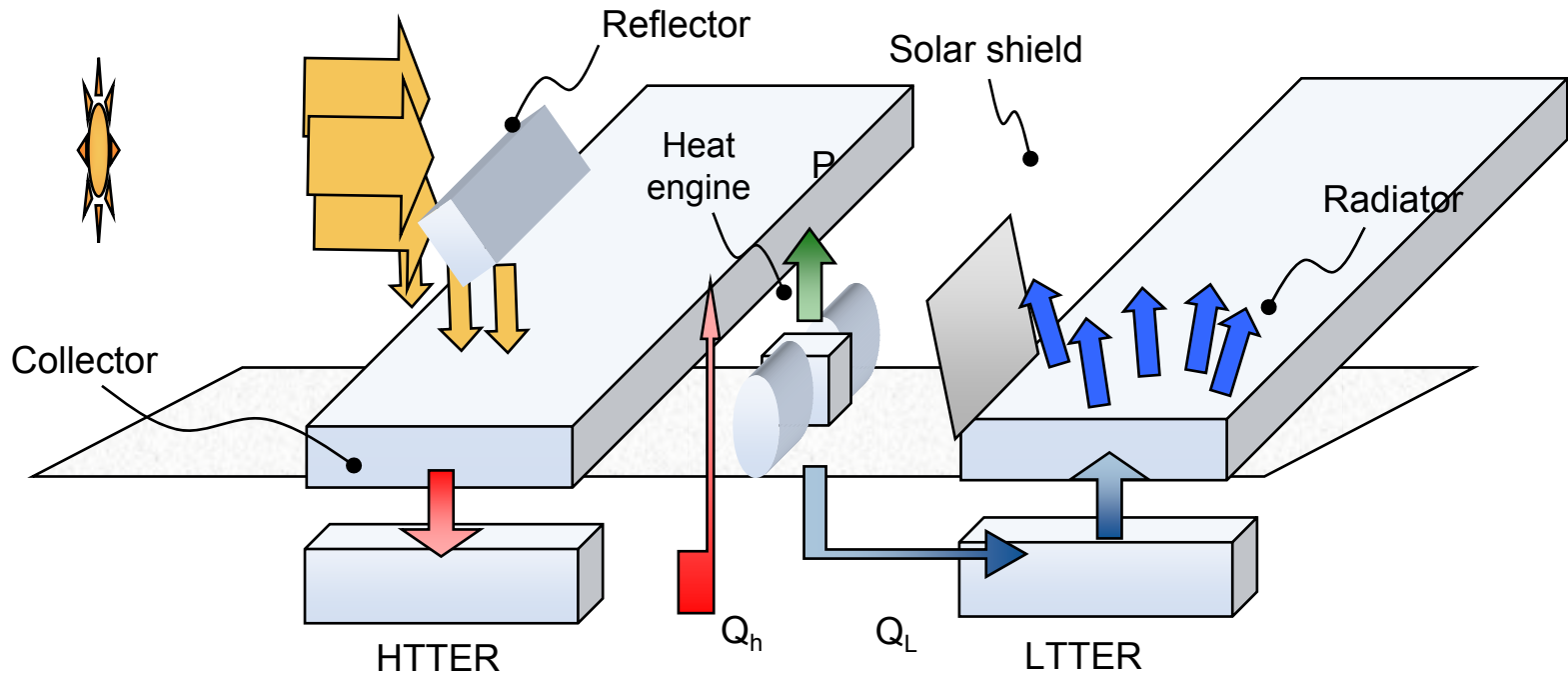
Reference case: Reflector, collector, HTTER, Carnot engine, radiator.

• No LTTER

• Alternate case: LTTER found favorable in previous work.

• Start with generally ideal assumptions for example calculations.

• Optimized the collector and radiator area for each HTTER, LTTER combination.

Solar Collector

- **Collector**: flat plate heat exchanger
  - Stamped from two 1 mm Al sheets
  - H_2 heat transfer gas from collector to HTTER.
  - Selective surface. Absorptivity =.9, IR emissivity = 0.1
- **Reflector** directs concentrated sunlight to the heat exchanger
  - Assume a 1mm Al sheet with 10 kg for tracking drive and 10 kg for supports.
  - Area=1.2*Concentration Ratio * Area Collector. Reflector and concentrator are combined for our low concentration ratios.
  - 2.7 kg/m^2
  - More advanced concentrators are possible.

High Temperature Thermal Energy Reservoir

- For the system model, assumes a thermal mass maintained at a uniform temperature by the flow of heat transfer fluid through the regolith.

- Component models examined this more carefully.

  – Regolith spheroids arranged within the propellant tank

- Assume the HTTER is a cube of dimension L, surrounded by a insulating radiation shield blanket.

  – Blankets can have effective emissivities ≈ .001 - .005.

- Neglected heat loss in our simulations, except for the seasonal simulations.

- Uncertainty in regolith properties. Varies with lunar location.

- Processed regolith - Used correlations of Colozza (1991), based on Apollo 17 data.

Stirling Technology

- Lee S. Mason, "A Comparison of Fission Power System Options for Lunar and Mars Surface Applications, NASA/TM-2006-214120

- Stirling system has the lowest system mass and best specific power
    - TE: 6.0 W/kg
    - Brayton: 8.8 W/kg
    - Stirling: 9.4 W/kg

- Stirling system has best overall efficiency
    - TE: 4.3%
    - Brayton: 13.9%
    - Stirling: 19.0%

- Stirling has broad operating range and can function effectively over temperature ratios as low as 2.0-2.5
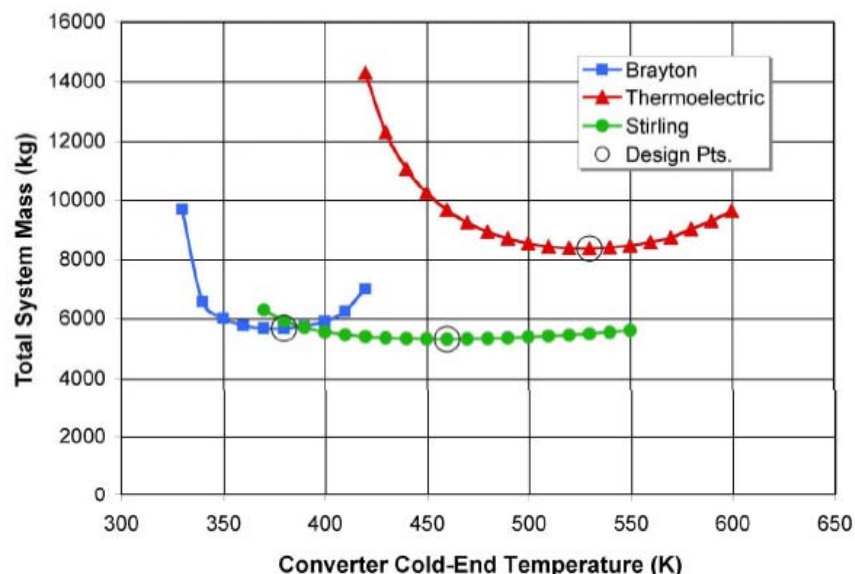
- Stirling: 60 % Carnot for $3 > T_H/T_L > 2$

- Brayton: 40 % Carnot for $4 > T_H/T_L > 3$

- Thermoelectric: < 20 % Carnot for $2 > T_H/T_L > 1.5$

- Stirling: ~ 100 W/kg

- (Mason and Schreiber, 2007)

- Stirling has run to $T_H/T_L \approx 1.5$. Assumed 1.25 for the analysis. No upper limit.

Radiator

- Two 1 mm sheets of Al
- Area density of 5.3 kg/m^2.
- 5 kg/m^2 used by others (Kohout, 1991; Freeh, 2008)
- Sink temperature assumed to be 10 K, with one side of active area.
- Mason has looked at vertical two-sided radiators with higher effective sink temperatures.
- Inflatable radiators ~ 1 kg/m^2 (Wong, GRC).

Low temperature thermal reservoir

- Can reduce radiator size

- In contrast to HTTER, we want to maximize heat loss. This implies large surface to volume ratio and low surrounding temperatures.

- Located in the shadows or cooled by heat rejection to dark sky at ≈ 10 K.

  - Summer or winter.

- Assumed to start at 150 K.

- Shadowed base of Shackleton crater ≈ 90 K, according to recent Japanese measurements.

Parasitic Power

- Four heat transfer loops using H_2.
  - Collector to HTTER
  - HTTER to engine
  - Engine to LTTER
  - LTTER to radiator
- Why hydrogen?
  - Excellent heat transfer properties
  - Low density is overcome by 10 atm operation.
  - Available from outpost
  - Other gaseous mixtures could be explored
  - Liquids like water are heavy: high launch mass.
- Four compressors: 15 kg each.

Stirling & loop pump package

L_{HTTR}

HTTR

L_{LTTR}

LTTR

L_C

L_R

Radiator

Collector
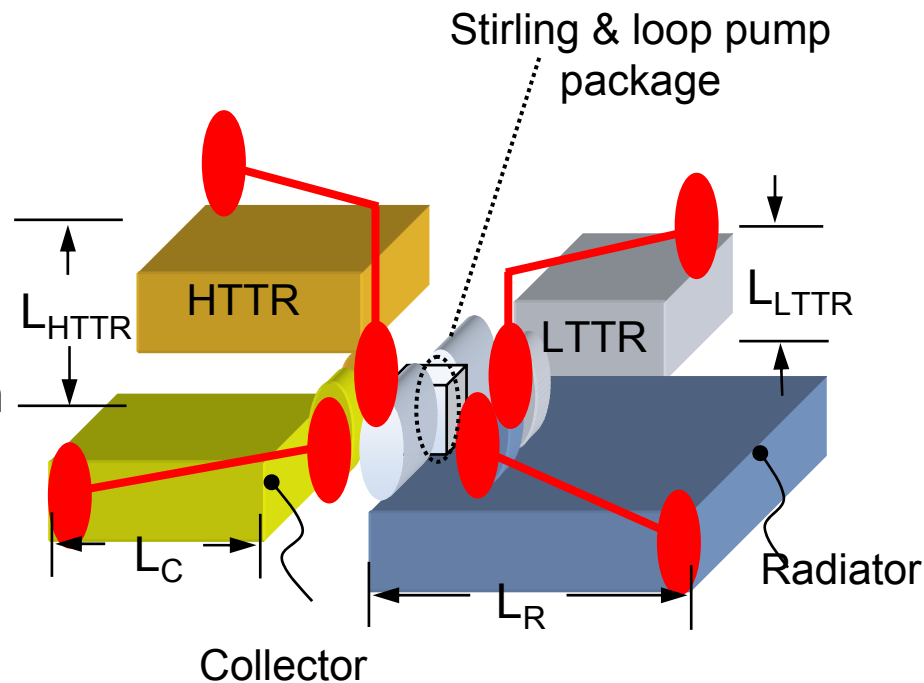
System Analysis

- Calculates energy performance and temperatures over the lunar day and night.

- Careful check of energy balances.

- System cycled through 10 day/night cycles to achieve steady-state. Tabulated energies on last cycle.

- Varied (Ac, Ar) to get maximum power density for each HTTER, LTTER combination.

- Found maximum power density for two cases:

  – T_L > 270 K. Usual operation is T_L≈ 323 K.

  – Any T_L
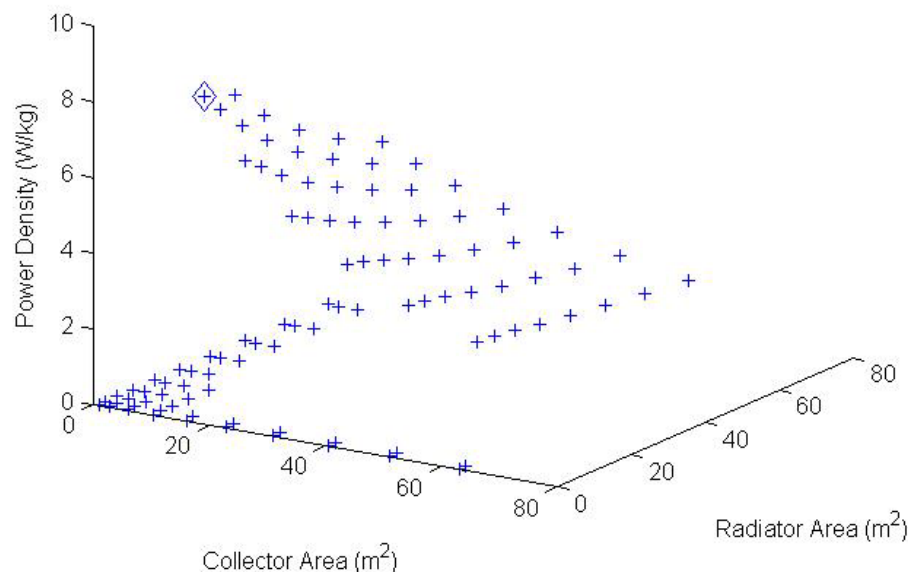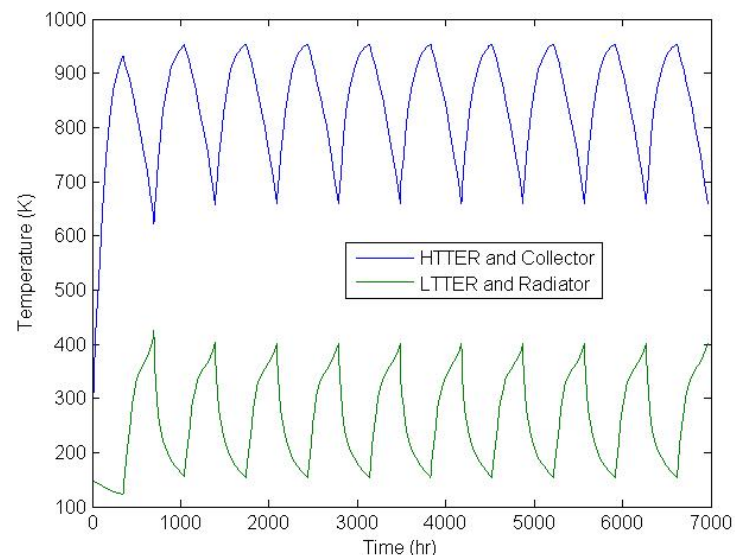
Overall Power Density

- Each point represents an optimized power density with collector and radiator area as the independent variables.

- 10,000 kg low temperature reservoir for all cases.

- Power is the shaft power (2440 W), not the net electrical power (2000 W).

- Parasitic power is roughly sized for 200 W.

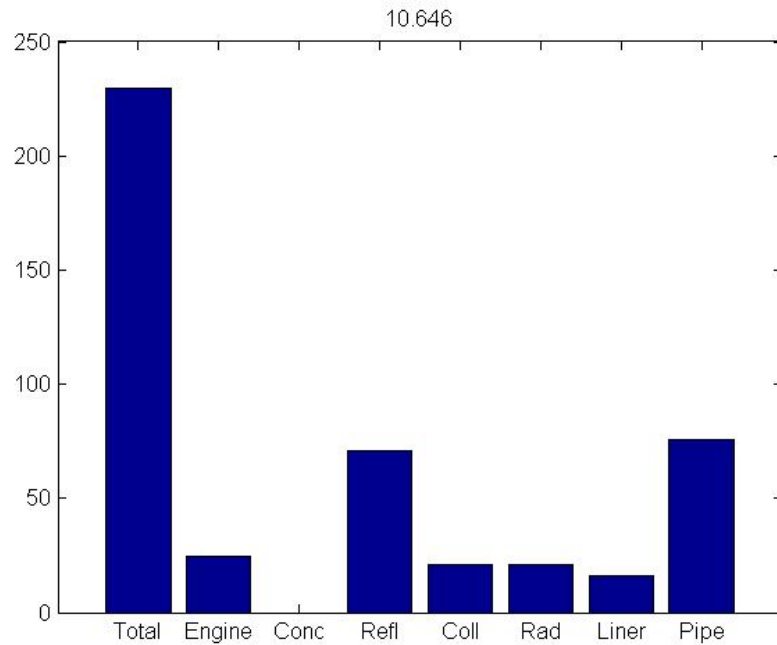- Temperature drop in heat transfer loops is about 10 K.
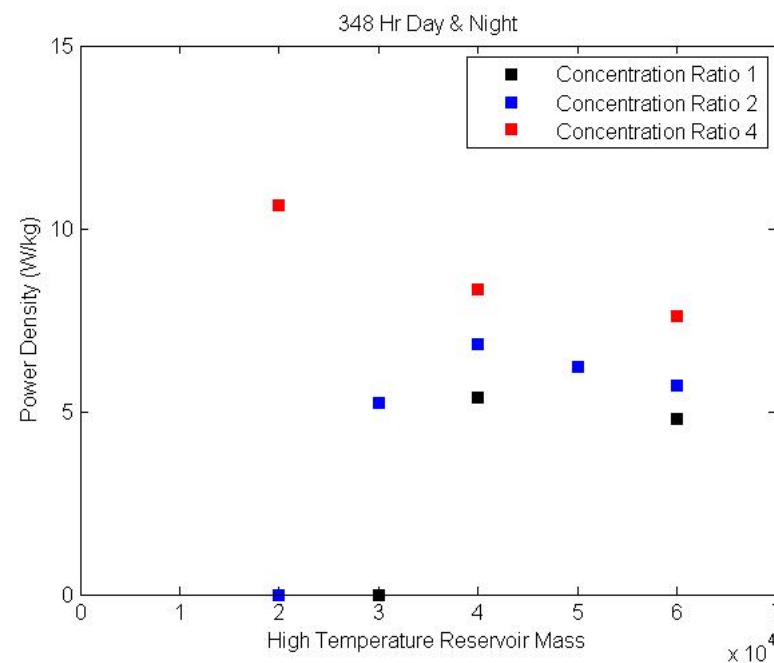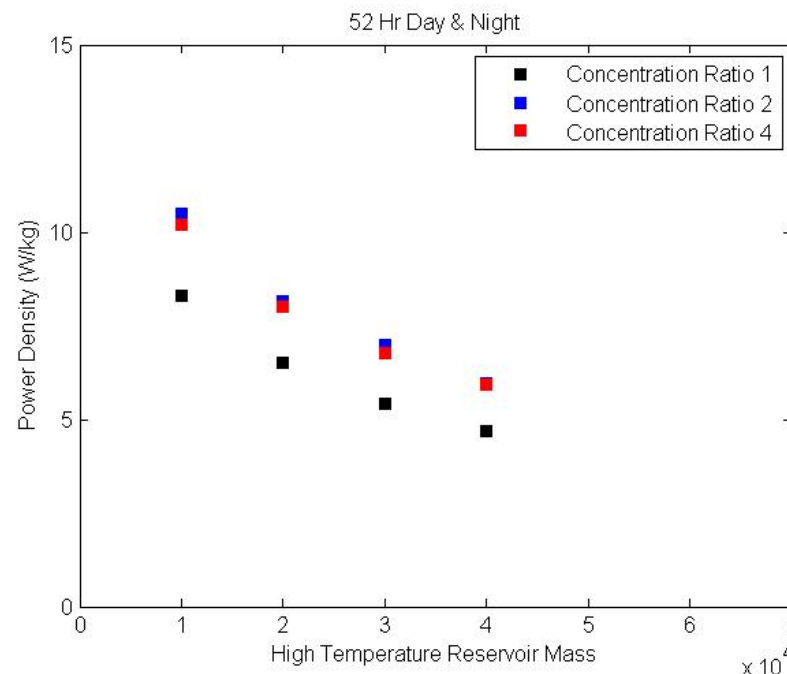
Mass, Temperature and Energy Flows
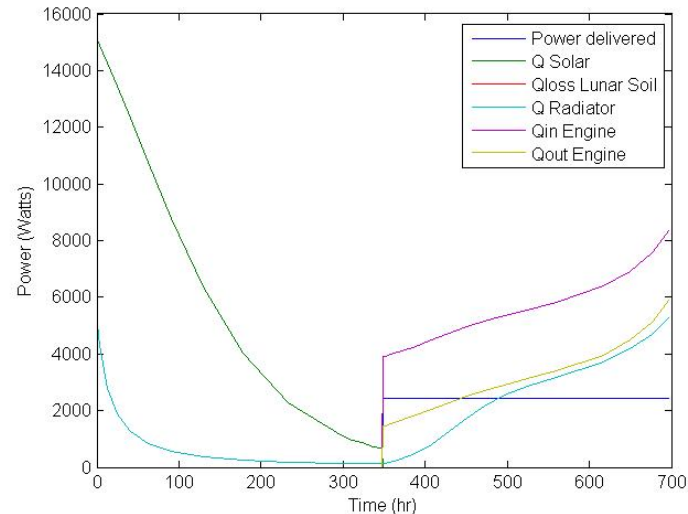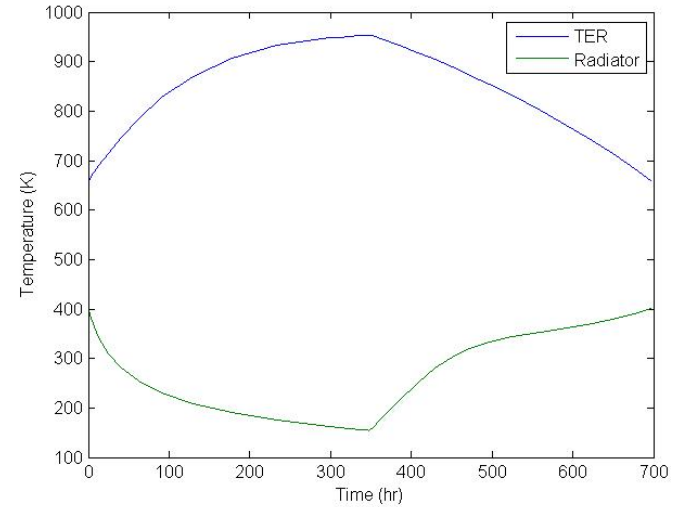
348 hr day and night

Solar concentration ratio = 4

20,000 kg HTTER.

System and component masses (kg)

Component sizing changes with location on the moon.

Seasonal Simulation

- Can we increase the power density by heating through the longer lunar daytime?

- Used GRC Shackleton data from Jim Fincannon. One 52 hr night. Long daylight periods

- Heatup in summer. No power withdrawal. As soon as sun drops below 10 % illumination - power on.

- Did not try to find best collector and radiator areas. Just reduced Ac from 348 hr result.

- 20,000 kg HTTER, 10,000 kg LTTER, concentration=4

- Power density = 14 W/kg, heat loss included.
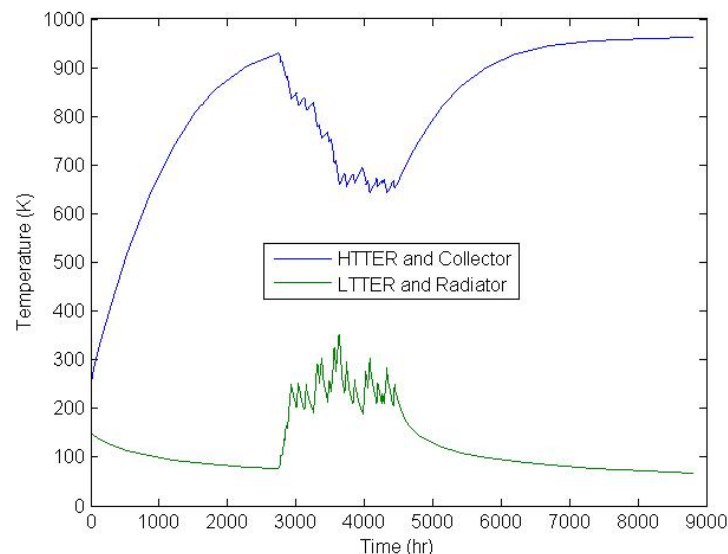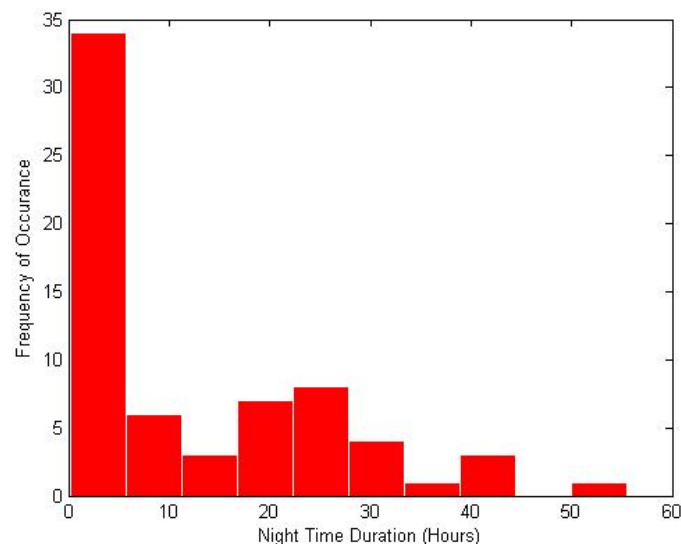
Summary for 2 kW$_e$ unit

	52 hr day/night	348 day/night	Seasonal simulation at the Shackleton Site
Net Power Density (W$_e$/kg)	8	9	11
Power Density (W$_{shaft}$ /kg)	9.5	10.7	14
Mass HTTER (kg)	10,000	20,000	20,000
Mass LTTER (kg)	10,000	10,000	10,000
Collector Area (m^2)	9.7	4	1
Concentration Ratio	2	4	4
Radiator Area (m^2)	2.5	4	4
Mass Carried (kg)	256	230	171
Engine (kg)	24.4	24.4	24.4
Reflector Mass (kg)	82.1	70.9	32.8
Collector Mass (kg)	51.7	21.2	5.3
Radiator Mass (kg)	13.3	21.2	21.2
Insulation Mass (kg)	10	15.9	15.9
Piping, Compressor, Mass (kg)	74.6	75.9	70.9

Using the Lander Tanks
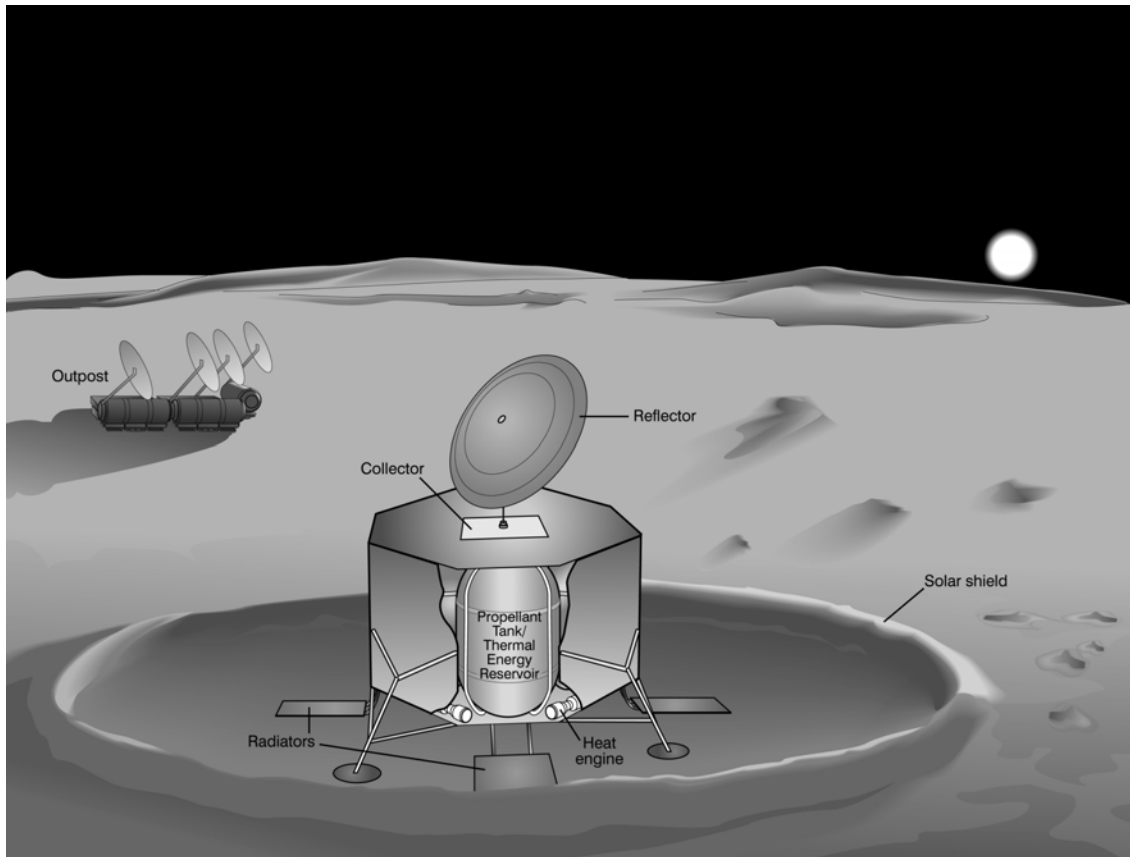
- Analysis showed that 20,000 kg on the HTTER and 10,000 kg on the LTTER would be sufficient for 2 kW_e.

- Capacity of 8 kW_e available using 4 H_2 and 4 O_2 lander tanks.

Recommended areas for future work

- Low mass concentrator-reflector-collector with high collection efficiency.

- Low mass radiator

- Processed regolith methods of production and properties.

- Review status of gas compressor or blower for heat transfer loops. Consider gas mixtures. Process design to minimize parasitic power.

- Lander tank modifications for use in thermal reservoirs.

- Update model and optimize power density. Include heat transfer loops to enable separate calculation of collector, HTTER, LTTER, and radiator temperatures.

- Determine operating temperatures for Stirling engine in this application.

- Control schemes.

Alternative Applications of Lunar TERs (not part of BAA project scope)

- Outpost TERs
  - Heat Engine / Electrical Power Generation during sunlight
  - Direct use of TM Heat Sources, Sinks
    - Thermal Integration of the Outpost
    - Temperature Moderation/Protection of Outpost Assets

- "Satellite" TERs
  - Electrical Power Generation for distributed assets (e.g., robotic International Lunar Network)
  - Heat for rovers and other assets (i.e., Thermal Wadis)

Conclusions

- TER Energy Storage / Power Generation at the Lunar Outpost is feasible
  - Depends largely upon applying technologies that are already developed or are in development
  - And using byproduct materials from ISRU oxygen production
- If the tankage of an Altair Lunar Lander is used to house TM materials
  - Electrical generation capacity: 8 kW_e
  - Net Power Density: 8-11 W_e/kg
- Concept is modular and scalable – can be used anywhere on the Moon
- Additional system studies and technology development is needed
  - Including studies to assess the feasibility of dual-use for the Altair descent stage